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Suitability of siloxanes for a mini ORC turbogenerator based on high-speed technology

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Background

– Nowadays most of the commercial ORC plants are in size of 100 kW – several MW

– However, there are many energy conversion applications where a really small sized ORC energy converter with power output of ca. 10 kW could be feasible.

  - Heat recovery from prime movers (micro gas turbines and small internal combustion engines (ICE))

  - Concentrated solar power applications

  - Small scale cogeneration of heat and power (e.g. domestic use)

– One of the key issues in designing a small-scale ORC is the selection of a suitable working fluid.

Siloxanes as ORC working fluids (1)

- Siloxanes are a family of organic compounds that contain silicon, oxygen and hydrocarbon group.

- Siloxanes have been successfully adopted in high-temperature ORC power plants for larger power capacities (400 kW_e – 2 MW_e).

- Advantages of siloxanes:

  - Low/non-toxicity
  - Good thermal stability
  - Limited flammability
  - Good thermodynamic properties in high and medium temperature applications (critical point, dry expansion etc.)
  - Good lubricating properties

Siloxanes as ORC working fluids (2)

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- Applicability of eight siloxanes for a small scale (10 kWe) ORC energy converter based on high speed turbogenerator technology were studied

- Cyclic siloxanes:
  - D4 (octamethylcyclotetrasiloxane, $C_8H_{24}O_4Si_4$)
  - D5 (decamethylcyclopentasiloxane, $C_{10}H_{30}O_5Si_5$),
  - D6 (dodecamethylcyclohexasiloxane, $C_{12}H_{36}Si_6O_6$)

- Linear siloxanes:
  - MDM (octamethyltrisiloxane, $C_8H_{24}Si_3O_2$),
  - MD2M (decamethyltetrasiloxane, $C_{10}H_{30}Si_4O_3$),
  - MD3M (dodecamethylpentasiloxane, $C_{12}H_{36}Si_5O_4$),
  - MD4M (tetradecamethylhexasiloxane, $C_{14}H_{42}O_5Si_6$),
  - MM (hexamethyldisiloxane, $C_6H_{18}OSi_2$)

ORC process based on high-speed turbogenerator technology

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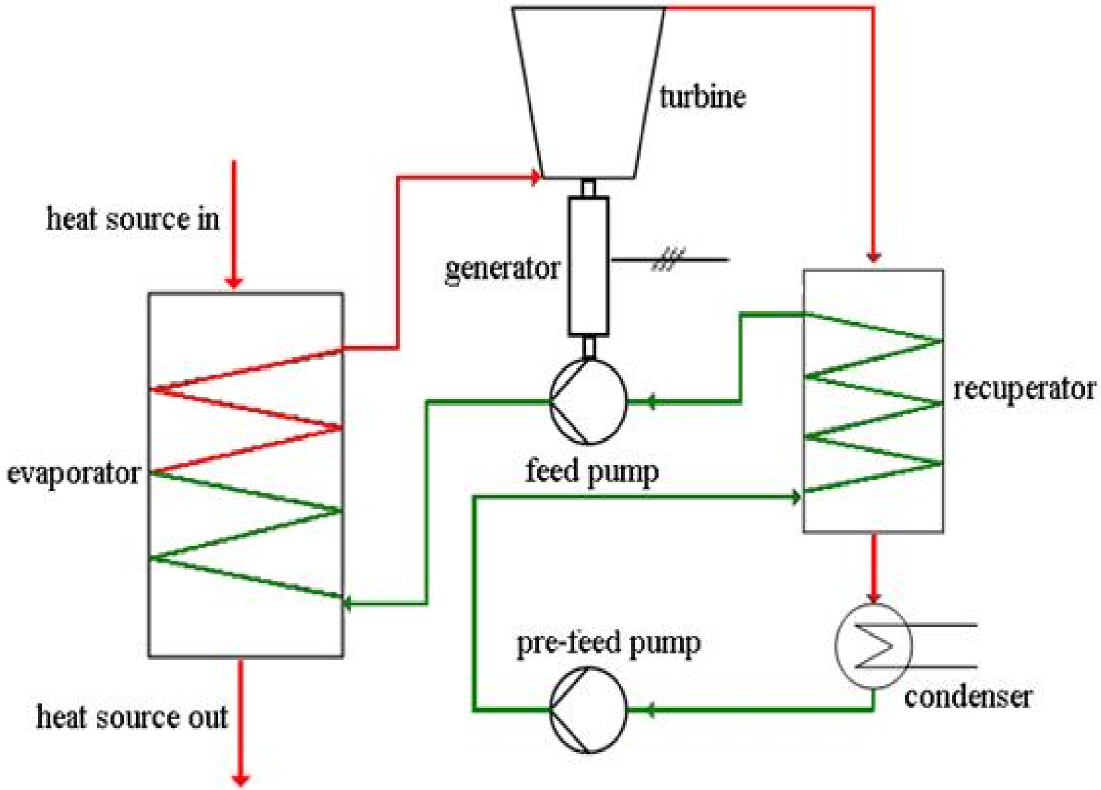
The high-speed turbogenerator refers to a hermetic system where the turbine, generator, and feed pump are directly coupled on the same shaft, having a high rotational speed, typically more than 20 000 rpm, and using working fluid lubricated bearings.



Calculations

- The effects of adopting different siloxanes on the thermodynamic cycle configuration, conversion efficiency, and on the turbine and component design were studied by means of computations

- Toluene is included in the process calculations as a reference working fluid

- Calculations were performed with an ORC calculation application developed at LUT. The applications uses RefProp 9.0 (developed by National Institute of Standards and Technology) in determining siloxane properties.

- The known properties of ORC processes using high-speed technology were based on the previous studies and plants tested at LUT (pressure losses, evaluated component efficiencies etc.)

- The selected rotational speed range of the turbogenerator was set to 20 000 – 60 000 rpm.

Calculations: component efficiencies and boundary conditions

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Table 1. *Heat source properties*

Mass flow rate, [kg/s]	0.227
Temperature before ORC, [^{o}C]	431
Temperature after ORC, [^{o}C]	210
Heat rate, [kW]	55.36

Table 2. *Component efficiencies and temperatures used in the process calculations*

Turbine efficiency, [%]	80
Generator and mechanical efficiency, [%]	92
Electric power output to grid, [%]	96.5
Main feed pump efficiency, [%]	50
Minimum degree of superheating,[^{o}C]	10
Turbine inlet maximum temperature, [^{o}C]	325
Condensing temperature, [^{o}C]	48.9
Degree of recuperation in recuperator, [-]	0.60 - 0.68

Calculations: critical temperatures and pressures based on RefProp 9.0

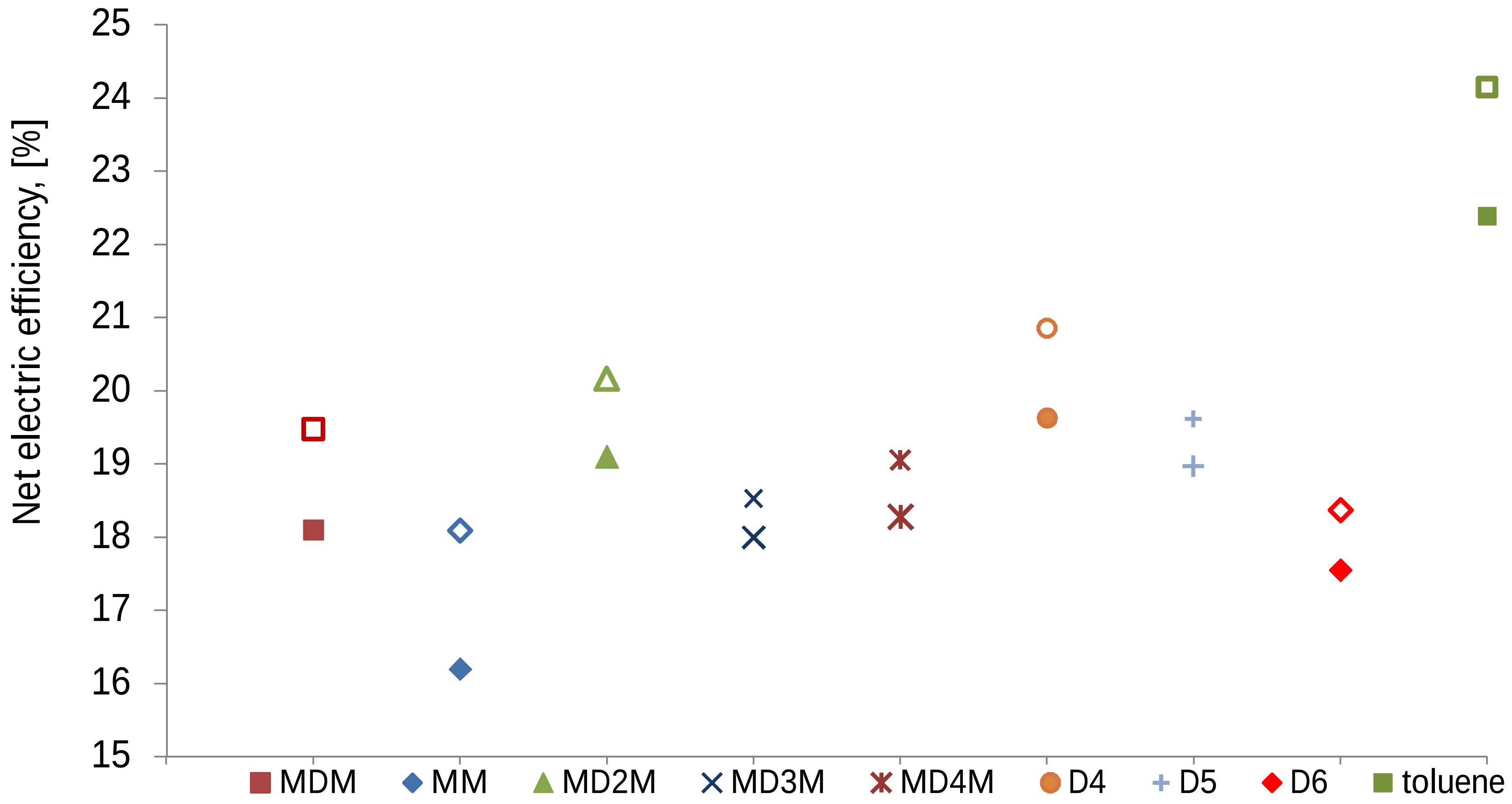
Table 3. *Critical pressures and temperatures of siloxanes (RefProp 9.0)*

Fluid	p_{cr} [bar]	T_{cr} [°C]
MDM	14.15	290.9
MM	19.39	245.6
MD2M	12.27	326.3
MD3M	9.45	355.2
MD4M	8.77	380.1
D4	13.32	313.4
D5	11.6	346.0
D6	9.61	372.6

Table 4. *Working fluid temperatures and pressures at the turbine inlet and condensing pressures*

Fluid	T_t [°C]	p_t [bar]	p_c [mbar]
MDM	302	12.0	21
MM	260	18.0	167
MD2M	325	9.4	3
MD3M	325	4.8	0.5
MD4M	325	2.9	0.09
D4	325	12.5	7
D5	325	7.0	1
D6	325	3.7	0.2

Results (1): net electric efficiency



The higher values do not include pressure losses, and lower ones include evaluated pressure losses.

Results (2): net electric power

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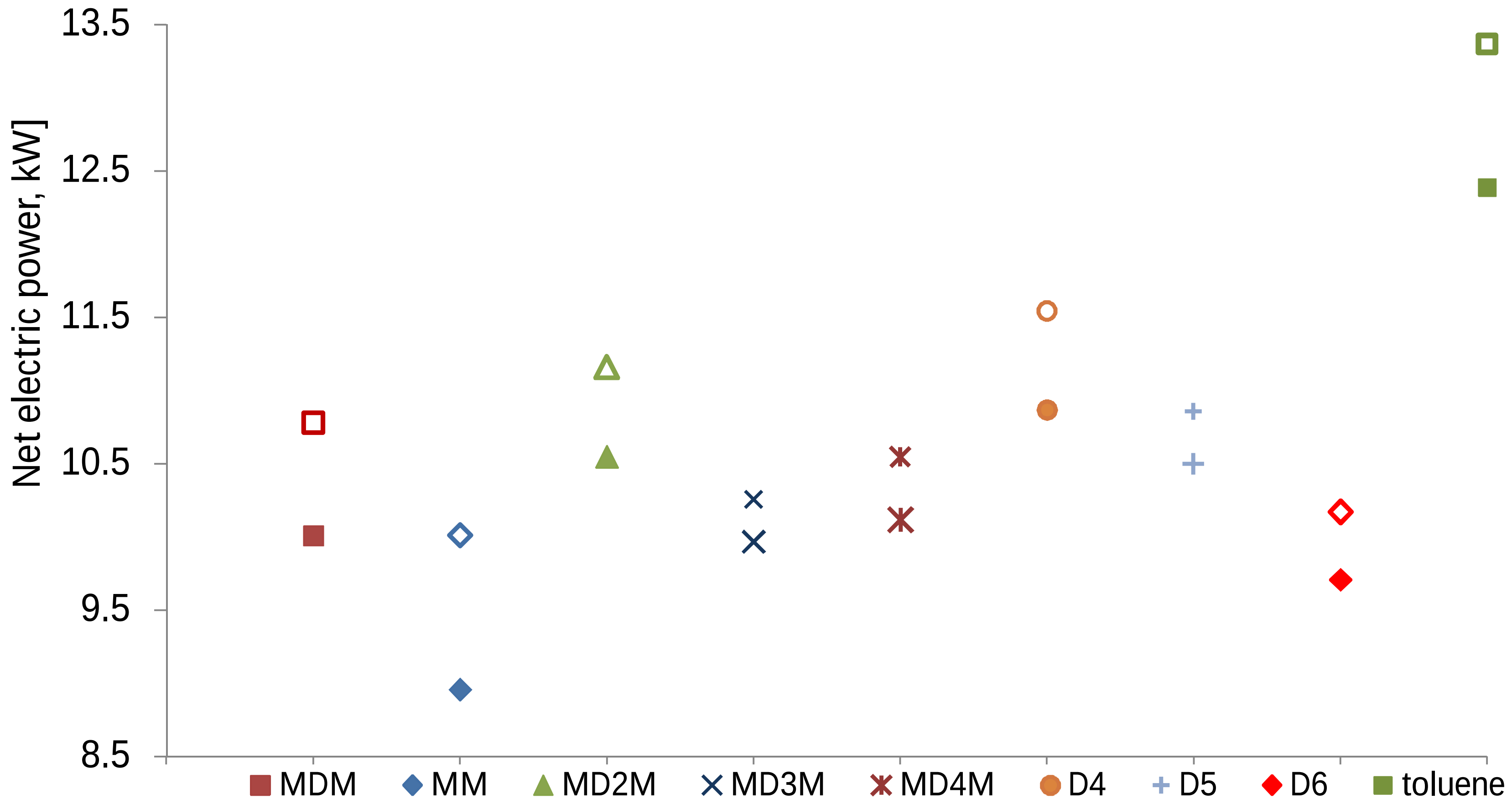
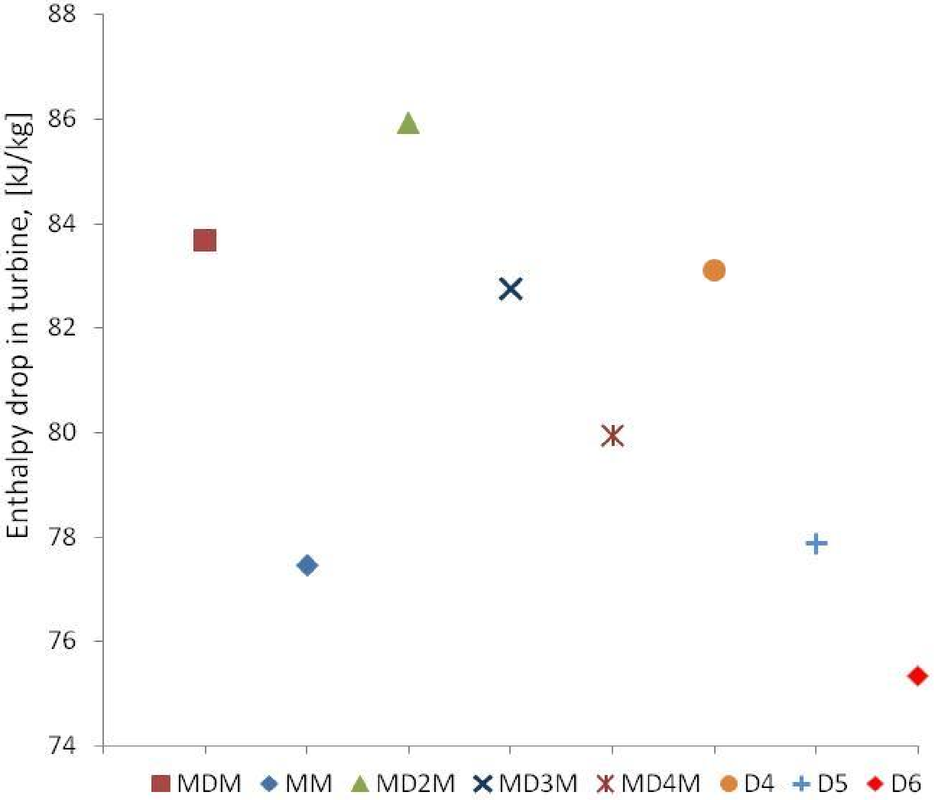
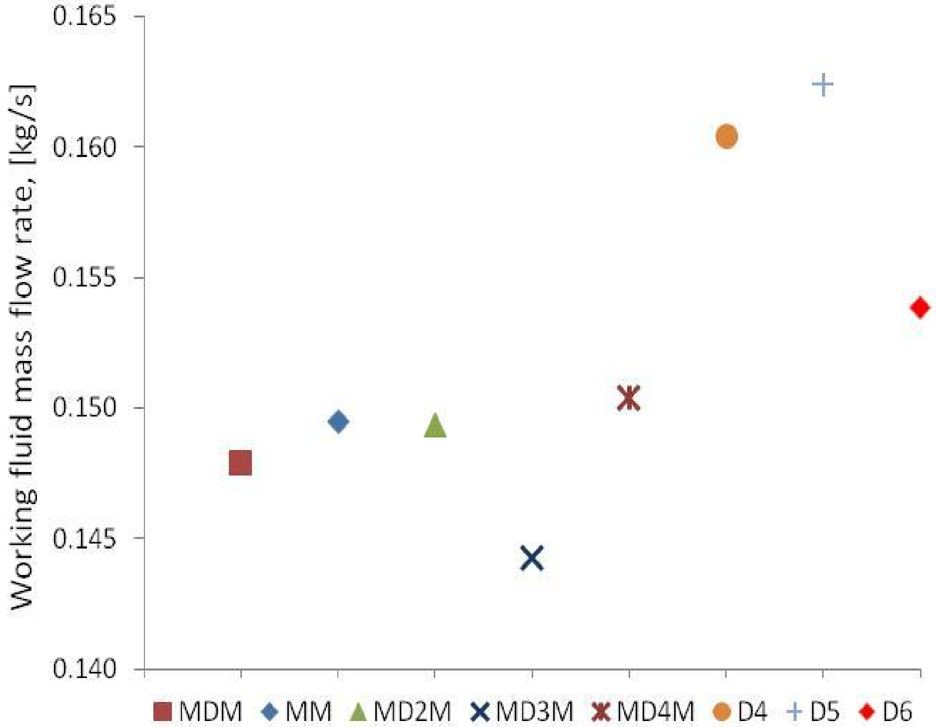


The higher values do not include pressure losses, and lower ones include evaluated pressure losses.

Results (3): enthalpy drop in turbine and mass flow rate





Enthalpy drop of toluene vapour in turbine: 175 kJ/kg, and mass flow: 0.09 kg/s

Turbine specific speed (Ns) with rotational speeds 20 000 – 60 000 rpm

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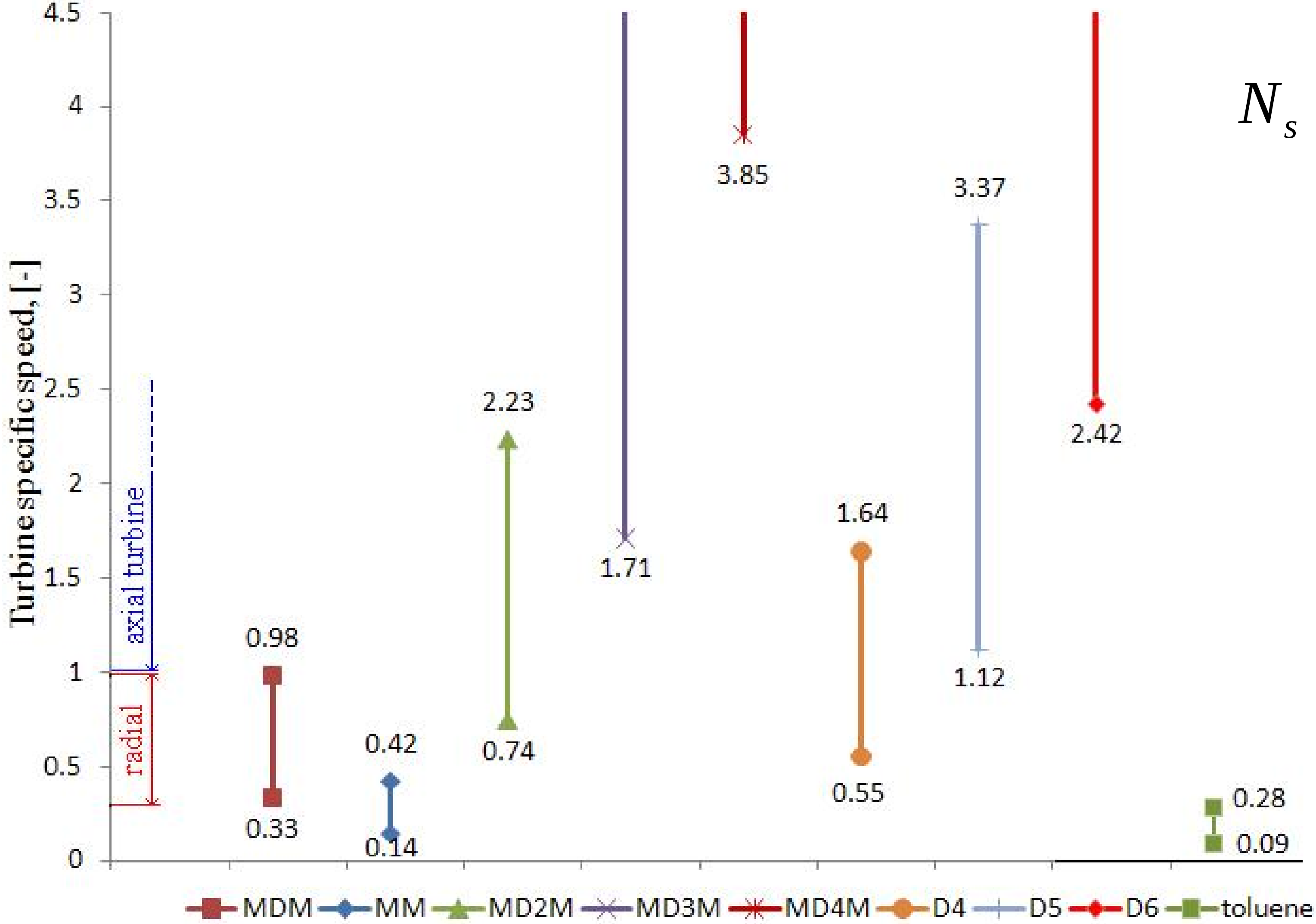
$$N_s = \frac{\omega\sqrt{q_v}}{\Delta h_s^{3/4}}$$



Discussions

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- Based on the results MDM and D4 were considered as the most suitable siloxanes:
  - Relatively high electrical efficiency
  - Reasonable condensing pressure
  - Suitable for single stage turbine design

- Also MD2M and D5 could be considered as suitable working fluids (lower condensing pressures compared to MDM and D4)

- Condensing pressures are less than 10 mbar with siloxanes MD2M, MD3M, MD4M, D4, D5 and D6 at the corresponding condensing temperature of 48.9 ^{o}C.

Discussions

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- Turbine specific speeds at selected turbogenerator rotation speed area shows that radial inward flow turbine would be a feasible choice in MDM, MM and D4 processes and axial turbine in MD3M, MD2M and D5 processes.

- Specific speeds are out of range for efficient turbine design in D6 and MD4M processes due to large volumetric flow at turbine outlet.

- Toluene process would have greater power output and cycle efficiency than siloxanes but the design of efficient turbine is not possible due to low values of specific speeds

- Further research will be centered on technological issues, such as material requirements, detailed process component design, as well as safety and reliability issues.

References

P. Colonna, N. R. Nannan, A. Guardone, 2008;
Multiparameter equations of state for siloxanes: $[(CH_3)_3\text{-Si-}O_{1/2}]_2\text{-}[O\text{-Si-}(CH_3)_2]i=1,...,3$, and $[O\text{-Si-}(CH_3)_2]_6$,
Fluid Phase Equilibria 263 (2008) 115–130.

P. Colonna, N. R. Nannan, A. Guardone, E.W. Lemmon; 2006.
Multiparameter equations of state for selected siloxanes,
Fluid Phase Equilibria 244 (2006) 193–211.

G. Angelino, C. Invernizzi, Cyclic methylsiloxanes as working fluids for space power cycles,
J. Sol. Energy—T. ASME 115 (3) (1993) 130–137.

Larjola J. ORC power plant based on high speed technology.
Conference on high speed technology, Lappeenranta, Finland, August 21-24, 1988

Larjola J.: Electricity from industrial waste heat using high-speed organic Rankine cycle.
International journal of production economics 41 (1995) 227-235, 1995

van Buijtenen J.P., Larjola J., Turunen-Saaresti T., Honkatukia J., Esa H., Backman J., Reunanen A.:
Design and validation of a new high expansion ratio radial turbine for ORC application.
5th European conference on Turbomachinery, Prague, March 17-22, 2003

van Buijtenen J.P.: The Tri-O-Gen Organic Rankine Cycle: development and perspectives,
Power Engineer March 2009 Volume 13 Issue 1, Journal of the IDGTE
(The Institution of Diesel and Gas Turbine Engineers)